

# Low-Temperature Gasoline Combustion (LTGC) Engine Research

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**John E. Dec**

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\* Now at General Motors



**June 6, 2017 – 12:00 p.m.**

**U.S. DOE, Vehicle Technologies Office  
Annual Merit Review and Peer Evaluation**

**Program Managers: Gurpreet Singh & Leo Breton**

**Project ID: ACS004**

*This presentation does not contain any proprietary, confidential, or otherwise restricted information.*

## Timeline

- Project provides fundamental research to support DOE/Industry advanced engine projects.
- Project directions and continuation are evaluated annually.

## Barriers / Research Needs

- Rapid control of LTGC / HCCI combustion timing
- Spark-Assisted LTGC / HCCI
- Advanced fuel-injection strategies
- Improved understanding of LTGC fundamentals

## Budget

- Project funded by DOE/VTO:
- FY16 – \$675k
- FY17 – \$665k

## Partners / Collaborators

- Project Lead: Sandia  $\Rightarrow$  John E. Dec
- Part of Advanced Engine Combustion working group – 15 industrial partners
- General Motors – in-depth collaboration
- ANL – fuel economy impact
- LLNL – UQ analysis
- LLNL – support kinetic modeling
- Co-Optima Fuels project
- Chevron – advanced fuels for LTGC
- Sandia LDRD – fuel injection

# Objectives - Relevance

**Project Relevance:** LTGC engines can provide efficiencies at or above diesel engines, with very low NOx & PM  $\Rightarrow$  potential to use light distillates efficiently.

**Project Objectives:** 1) Provide the fundamental understanding (science-base) required for industry to develop practical LTGC engines.  $\Rightarrow$  2) Explore methods to exploit this understanding to overcome the technical barriers to LTGC.

- Relevant to both 1) LTGC / SI for Light-Duty, and 2) Full-time LTGC for LD, MD, HD

## **FY17 Objectives** $\Rightarrow$ Combustion Timing (CA50) Control is a Primary Focus

- Quantify the CA50 control range for LTGC engines using double-pulse fuel injection strategies for intake pressures ( $P_{in}$ ) from 1.0 to 2.0 bar and CRs of 14:1 and 16:1.
- Determine the range of conditions for which Spark-Assist (SA) can provide CA50 control for well-premixed LTGC.  
 $\Rightarrow$  Range of  $P_{in}$ s, intake temperatures ( $T_{in}$ ), and equivalence ratios ( $\phi$ )
- Compute Brake Thermal Efficiencies (BTEs) for a range of LTGC engine speeds and loads  $\Rightarrow$  Work w/ ANL to determine potential vehicle fuel-economy improvement.
- Conduct an Uncertainty Quantification (UQ) analysis in collaboration with LLNL.
- Support chemical-kinetics model development at LLNL.

## Combustion-timing control is a key technical barrier to LTGC

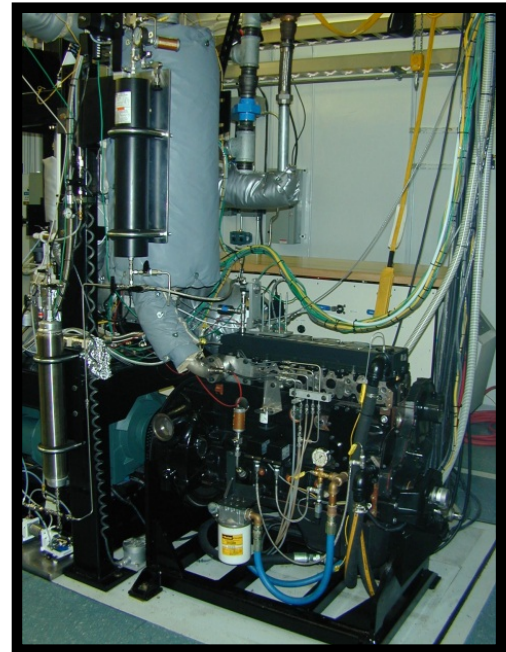
### ⇒ Investigate the two most promising methods

- **FY17:** Use Sandia single-cylinder all-metal LTGC engine, designed to allow well-controlled experiments.  
**Future:** Optical-engine imaging studies to better optimize.
- 1) Apply multi-pulse fuel injection strategies to adjust the chemical-kinetic rates of autoignition to control CA50.
  - Injection strategy ⇒ mixture distribution ⇒ autoig. timing
- 2) Spark-Assist to control CA50: Systematically vary  $P_{in}$ ,  $T_{in}$ ,  $\phi$  for premixed operation, to map out potential for SA ctrl.

## Other Tasks

- Compute BTEs by correcting indicated TEs for friction & turbocharger effects, using GM models. ⇒ Work with ANL to apply “Autonomie” model for vehicle simulations.
- UQ Analysis: Collaborate with LLNL (R. Whitesides & G. Petitpas) to evaluate the sources of uncertainty in experimental measurements, and how accuracy can be improved through good laboratory practices and rigorous calibrations.
- Kinetic-model development: Work with LLNL (B. Pitz & M. Mehl) to support their development of an improved kinetic model for RD5-87, a Regular-E10 gasoline.
- Transfer results to industry through presentations, discussions, and formal papers.

LTGC Research Engine





# Approach – Milestones and Project Goals

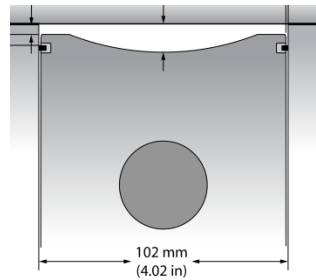
**DOE – Dashboard Milestone  $\Rightarrow$  Reviewed by DOE upper management**

- ✓ • **December 2016**  
Quantify the crank-angle range over which combustion timing can be controlled in advanced compression ignition (ACI) LTGC engines using multi-pulse fuel injection strategies to adjust kinetic rates of autoignition for  $P_{in}$ s from 1.0 to 2.0 bar and compression ratios (CR) of 14:1 and 16:1.  $\Rightarrow$  **Completed**

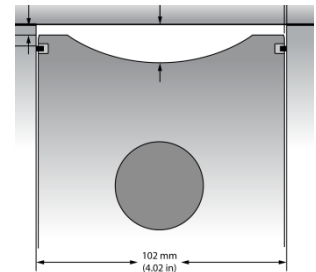
## **Project Goals**

- ✓ • **March 2017**  
Complete Brake TE calculations for selected conditions, and work with ANL to apply “Autonomie” model for vehicle simulations.  $\Rightarrow$  **Completed**
- ✓ • **April 2017**  
Complete SAE paper showing high efficiencies (above typical diesel levels) and high loads with intake boost similar to those of diesel engines (~20 bar IMEP<sub>g</sub> with 2 bar boost). Present at SAE Congress.  $\Rightarrow$  **Completed**
- ✓ • **September 2017**  
Determine the range of intake pressures and equivalence ratios for which spark assist can be used to control combustion timing of well-premixed LTGC.  $\Rightarrow$  **Substantial progress. On track to be completed as scheduled.**

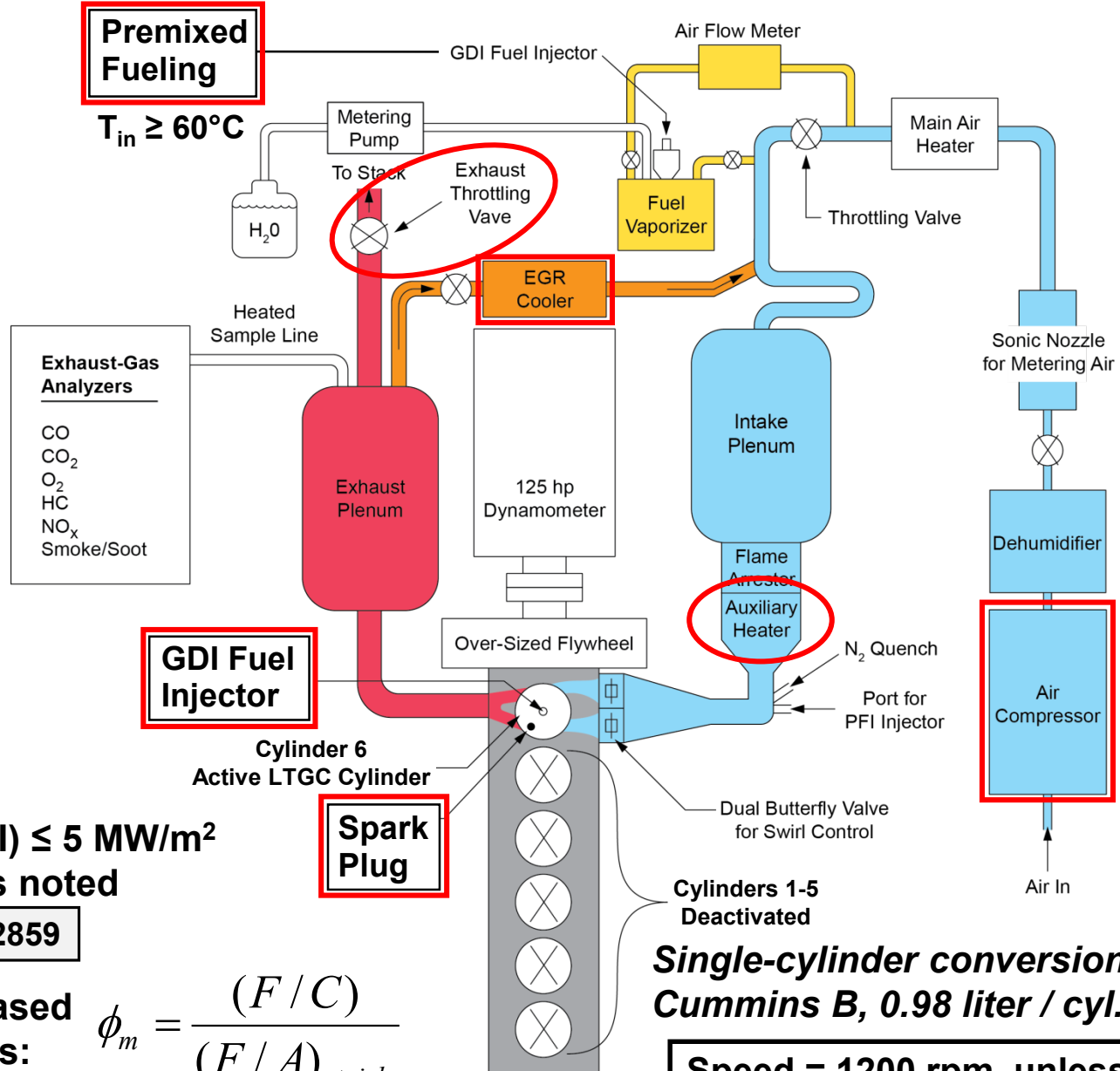
# LTGC (HCCI) Engine and Subsystems



**CR = 16 piston**



**CR = 14 piston**



- Ringing Intensity (RI)  $\leq 5 \text{ MW/m}^2$  for no knock, unless noted

Eng, SAE 2002-01-2859

- Equivalence ratio based on total charge mass:

$$\phi_m = \frac{(F/C)}{(F/A)_{stoich}}$$

**Single-cylinder conversion of Cummins B, 0.98 liter / cyl.**

**Speed = 1200 rpm, unless noted**



# Overview of Accomplishments

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- Quantified the crank-angle range for CA50 control in an LTGC engine using Double Direct Injection – Partial Fuel Stratification (DDI-PFS)  
⇒ Double-pulse fuel-injection strategy to adjust kinetic rates of autoignition.
  - Demonstrated CA50 control over a wide range
  - $P_{in}$ s from 1.0 to 2.0 bar
  - CRs of 14:1 and 16:1
- Showed that Spark-Assist (SA) works well for  $P_{in}$ s from 1.0 to 1.6 bar absolute.  
⇒ Determined the range of equivalence ratios ( $\phi_m$ ) for which SA can provide CA50 control and compensate for decreased  $T_{in}$  for well-premixed LTGC.
- Computed Brake TEs from indicated data for a range of speeds & loads.  
⇒ Worked with ANL to determine potential vehicle fuel-economy improvement.
- Collaborated w/ LLNL to conduct a UQ analysis of our pressure measurements.
- Supported LLNL on the development of a kinetic model for RD5-87, a Regular-grade E10 (Reg-E10) gasoline, 87 AKI.

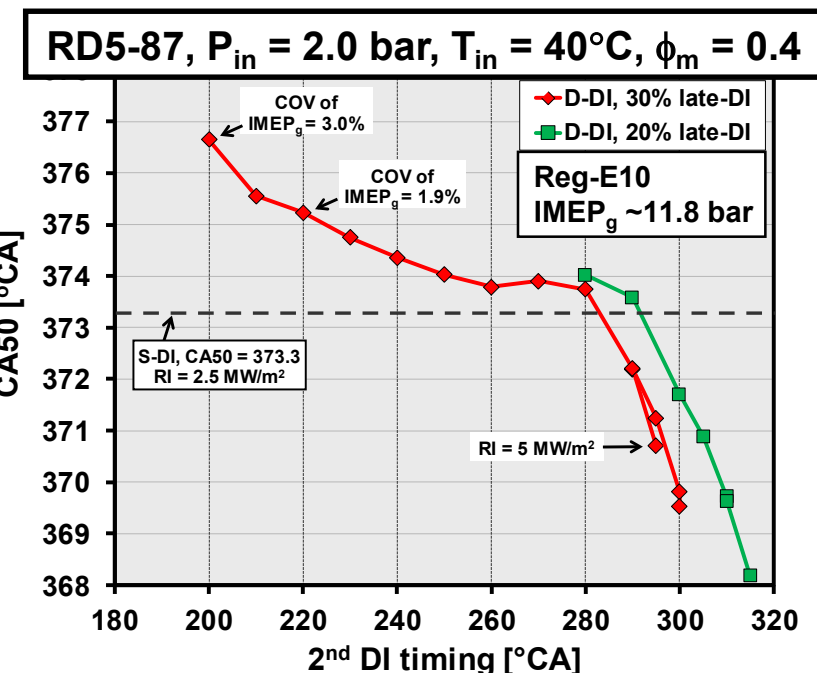
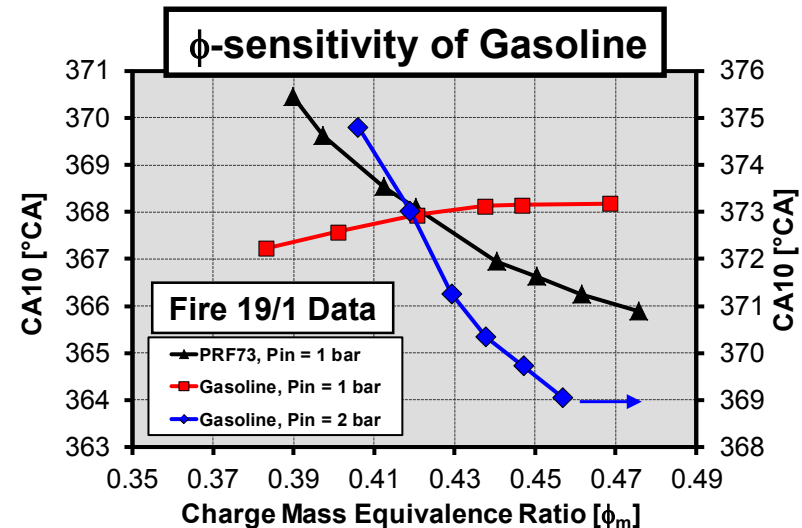
# Review: Injection-Timing/PFS to Control LTGC

- Many gasolines are  $\phi$ -sensitive, particularly with intake boost.  
 $\Rightarrow$  autoignition reactivity varies with the fuel/air equivalence ratio ( $\phi$ ).
- For stratified mixtures, faster autoignition of richer regions advances CA50.  
 $\Rightarrow$  Vary the stratification for CA50 control.
- Use a double-direct injection to produce desired partial fuel stratification (DDI-PFS)
  - Early injection sets min.  $\phi \Rightarrow$  good comb. eff.
  - Late-DI timing & fuel fraction adjust stratification.
- 2nd-DI timing of 200° CA gives a fairly well-mixed charge  $\Rightarrow$  CA50 is quite retarded.

- Retarding the 2nd-DI timing increases the  $\phi$  of the richest regions  $\Rightarrow$  advances CA50.
  - Can advance CA50 beyond the RI(knock) limit.

- 80/20% split allows even more CA50 advance.

- CA50 control authority is 8.5° CA.**

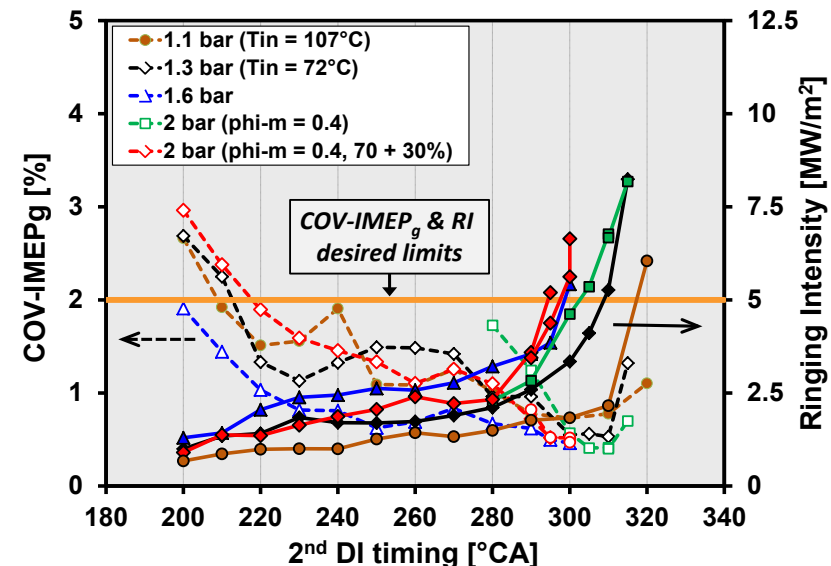
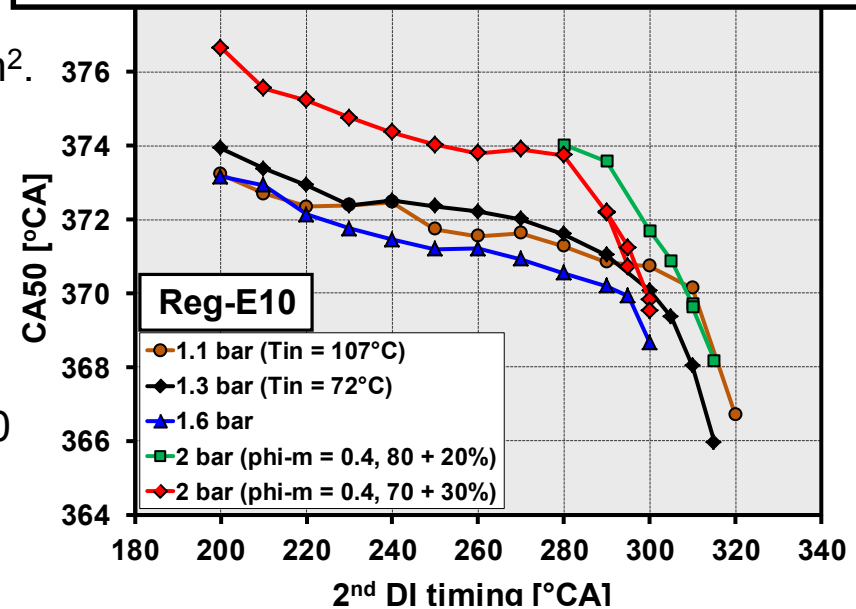


# CA50 Control w/ DDI-PFS: $P_{in} = 2.0 \Rightarrow 1.1$ bar

- DDI-PFS gives good CA50 ctrl at  $P_{in} = 2$  bar
  - Preferred:  $COV \leq 2\%$  COV and  $RI \leq 5$  MW/m<sup>2</sup>.
  - Can easily shift CA50 into desired range.
- Is DDI-PFS control effective at lower  $P_{in}$ s ?
  - Use  $\phi_m = 0.36$ , and 80% DI-60 + 20% late-DI
- Procedure:
  - For late-DI = 200° CA, adjust EGR for a CA50 giving a  $COV-IMEP_g = 2$  or 3%
  - Hold EGR constant and retard late-DI to advance CA50.
- CA50 control at 1.6, 1.3, and 1.1 bar is similar to 2.0 bar.
  - Curves are generally shifted to more advanced CA50s due to lower PRR at lower  $P_{in}$ s.

**DDI-PFS provides effective CA50 control for all  $P_{in}$ s from 2.0 to 1.1 bar.**

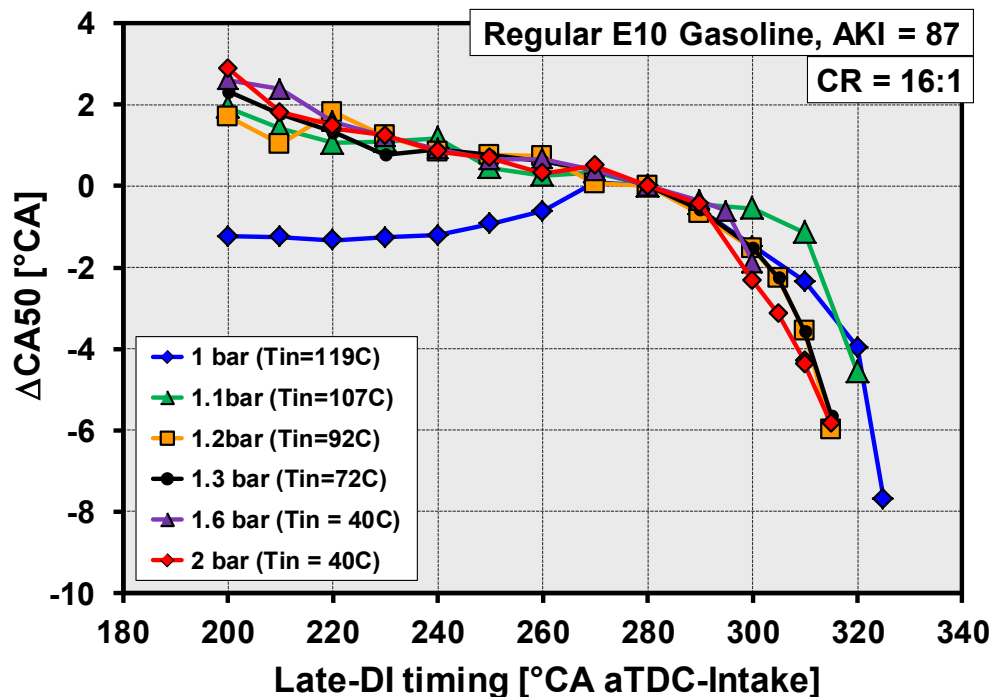
$T_{in} = 40 \text{ \& } 72^\circ\text{C}$ ,  $\phi_m = 0.36 \text{ \& } 0.4$ , DDI = 80/20%



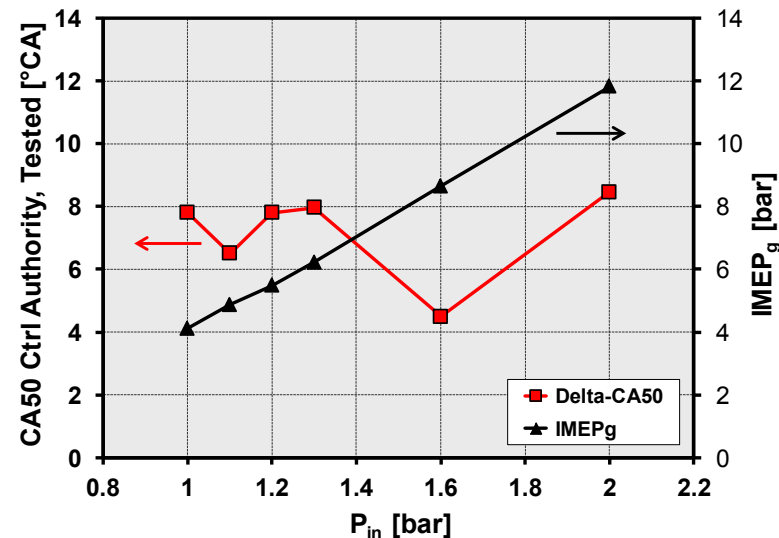


# CA50 Control w/ DDI-PFS: $P_{in} = 2.0 \Rightarrow 1.0$ bar, CR = 16:1

- For a better comparison, offset CA50 to align 2<sup>nd</sup> DI = 280° CA points, and plot only 80/20% data for later 2<sup>nd</sup>-DI timings at  $P_{in} = 2$  bar.
- Curves very similar**  $\Rightarrow P_{in} = 1.1$  bar req's a bit more strat. for strong CA50 adv.
- DDI-PFS also provides good CA50 control at  $P_{in} = 1.0$  bar** (nat. aspirated), but requires more stratification. Control effective for late-DI timings of 280 – 325° CA.
- DDI-PFS gives 6.5 – 8.5° CA of control authority for  $P_{in} = 1.0$  to 2.0 bar,**  
 $\Rightarrow$  except  $P_{in} = 1.6$  bar, only 4.5° CA, due to reduced stability.



- $IMEP_g$  varies from 4 to 12 bar for data presented here.

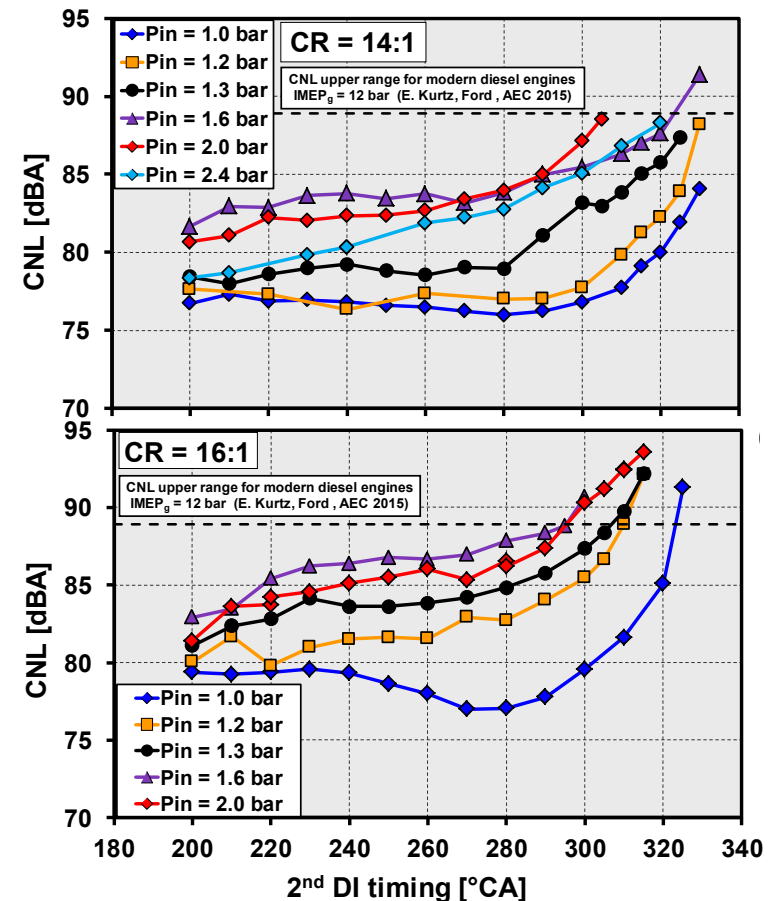
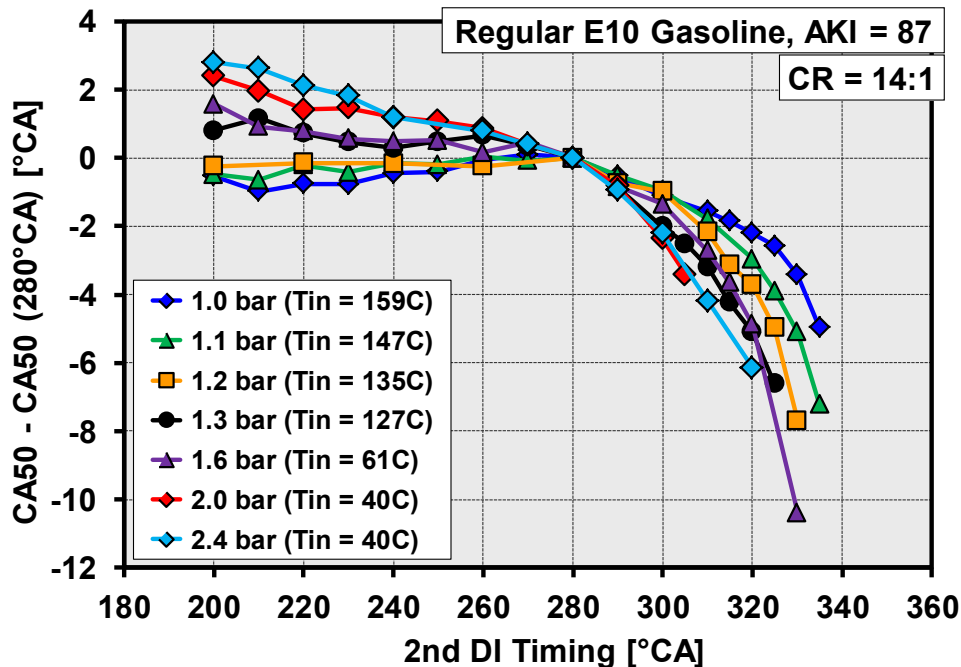




# CA50 Control w/ DDI-PFS: $P_{in} = 2.4 \Rightarrow 1.0$ bar, CR = 14:1

- DDI-PFS works well at CR = 16:1, but some designs favor CR = 14:1.
- DDI-PFS also works well for CR = 14:1. Trends similar to CR = 16:1.**  
 $\Rightarrow 6 - 9^\circ$  CA of CA50 control authority for  $P_{in} = 1.0$  to 2.4 bar.
- More stratification required at lower  $P_{in}$ s (later 2<sup>nd</sup>-DI timing)  $\Rightarrow$  probably due to reduced  $\phi$ -sensitivity because compressed-gas pressures are lower.
- CNL for DDI-PFS is below limits except for the most stratified points at both CRs.

— CNL generally lower for CR = 14:1.  
 $\Rightarrow$  CA50 advance limited by NOx

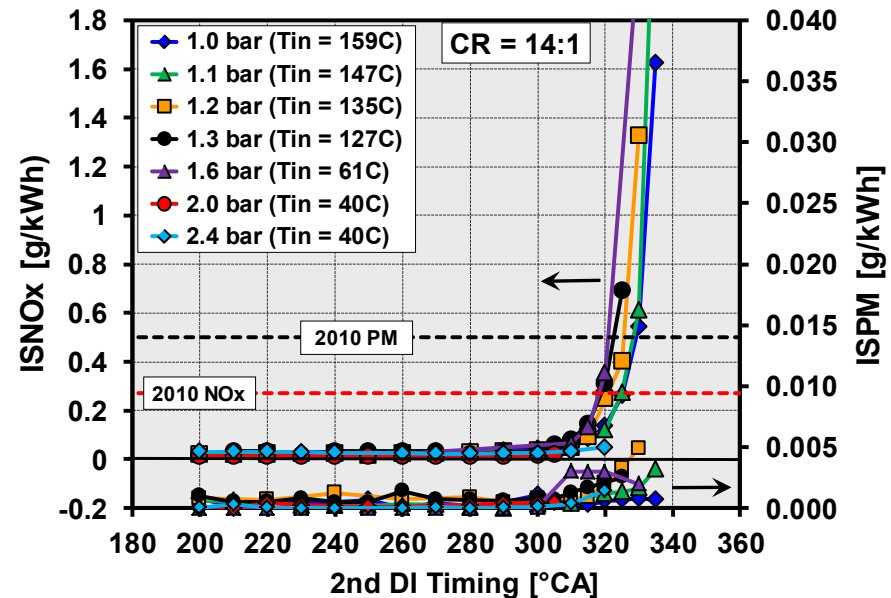
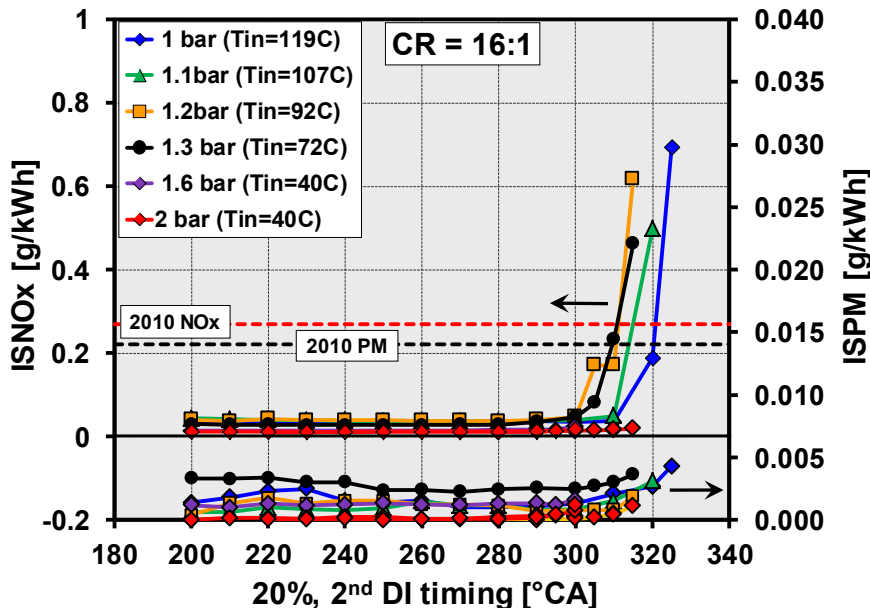




# NOx & PM Emissions for DDI-PFS Control Sweeps

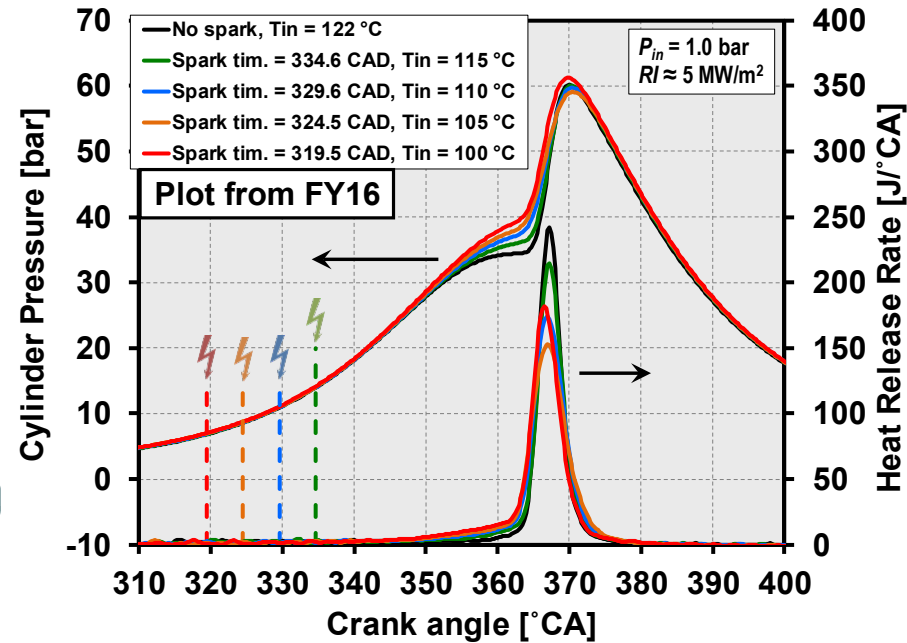
## CRs = 14 & 16:1

- PM (soot) emissions are very low, well below US2010 MD/HD stds. for both CRs.
  - CR = 16:1  $\Rightarrow$  NOx below US2010, except most stratified points with  $RI > 5\text{MW/m}^2$  for  $P_{in} \leq 1.3\text{ bar}$ , which require higher  $T_{in}$ .  $\Rightarrow$  Only a small effect on CA50 ctrl range.
  - CR = 14:1  $\Rightarrow$  NOx below US2010, until 2<sup>nd</sup> DI timing  $\geq 320 - 325^\circ\text{ CA}$ .  
 $\Rightarrow$  Still significant CA50 control in this range especially at higher boost.
    - Compared to CR = 16:1, lower  $P_{in}$ s require higher  $T_{in}$ s and more stratification to adjust CA50 to more advanced combustion timings.  $\Rightarrow$  Both factors act to increase NOx.
- More optimized fuel stratification expected to lower NOx and give better CA50 control, but some NOx aftertreatment may be required, particularly for CR = 14:1.

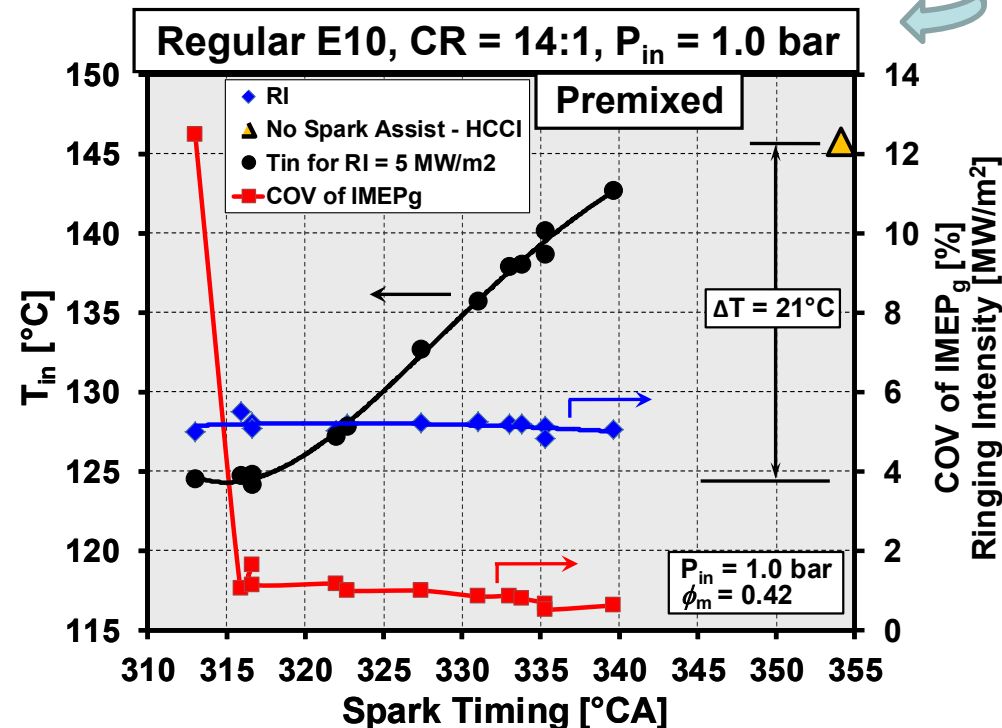


# Spark-Assist for LTGC Control, $P_{in} = 1$ bar

- Spark-assist (SA) is another a promising control method for LTGC.
- Spark initiates a flame that compresses remaining charge into autoig. as it burns.
  - Up to about 15% of the total HR for dilute LTGC conditions ( $\phi_m < 0.5$ )
- Can **compensate for reduced  $T_{in}$**  and/or provide CA50 control.  $\Rightarrow$  New Data

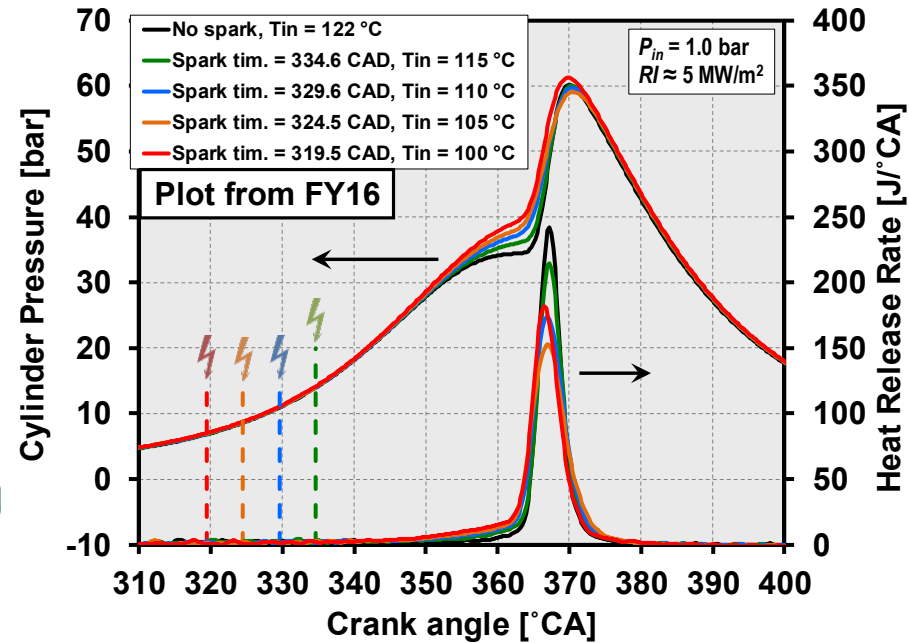


- For SA + CI, can reduce  $T_{in}$  up to  $21^\circ\text{C}$  and **maintain CA50 and RI & COV < 2%** by advancing spark timing.
  - Limited by misfire cycles, rapid COV  $\nearrow$
- For CI only,  $\Delta T_{in} = 3.6^\circ\text{C}$  from  $RI = 5$  MW/m<sup>2</sup> to COV-IMEP<sub>g</sub> = 2%
- SA greatly increases tolerance to  $T_{in}$  variation, from **3.6 to  $21^\circ\text{C}$** .



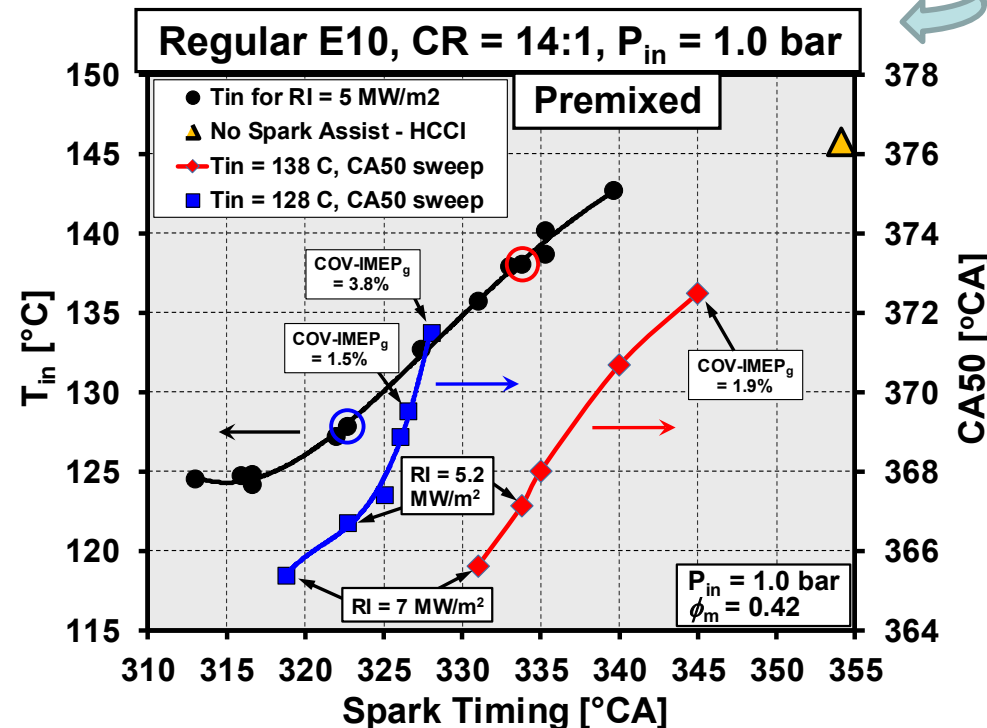
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  - Up to about 15% of the total HR for dilute LTGC conditions ( $\phi_m < 0.5$ )
- Can compensate for reduced  $T_{in}$  and/or **provide CA50 control**.  $\Rightarrow$  New Data



- For SA + CI at  $T_{in} = 138^\circ\text{C}$ , vary spark timing to **adjust CA50 up to 7° CA**.
  - $RI = 7$  MW/m<sup>2</sup> to  $COV-IMEP_g = 1.9\%$ .
- For lower  $T_{in} = 128^\circ\text{C}$ , spark-timing **control of CA50 reduced to 4° CA**.
  - $RI = 7$  MW/m<sup>2</sup> to  $COV-IMEP_g = 1.5\%$

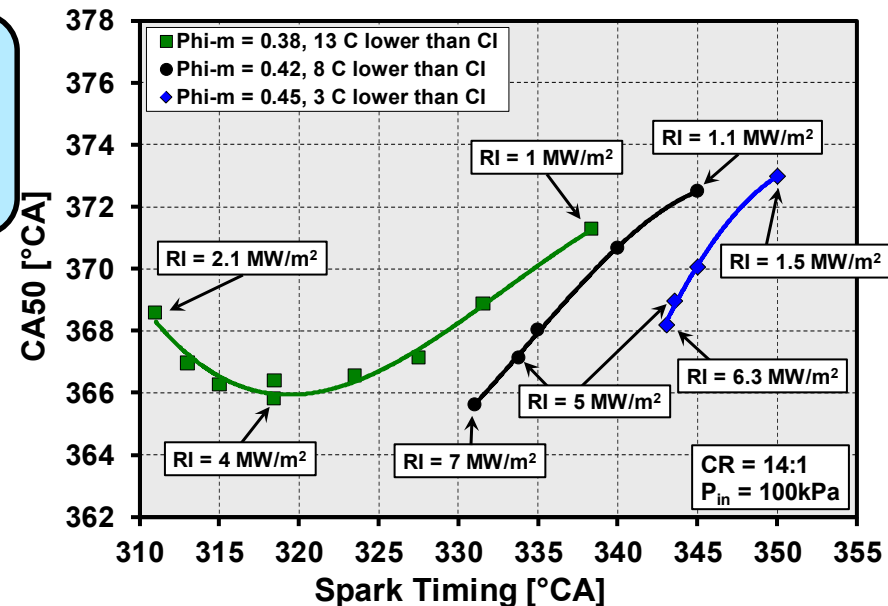
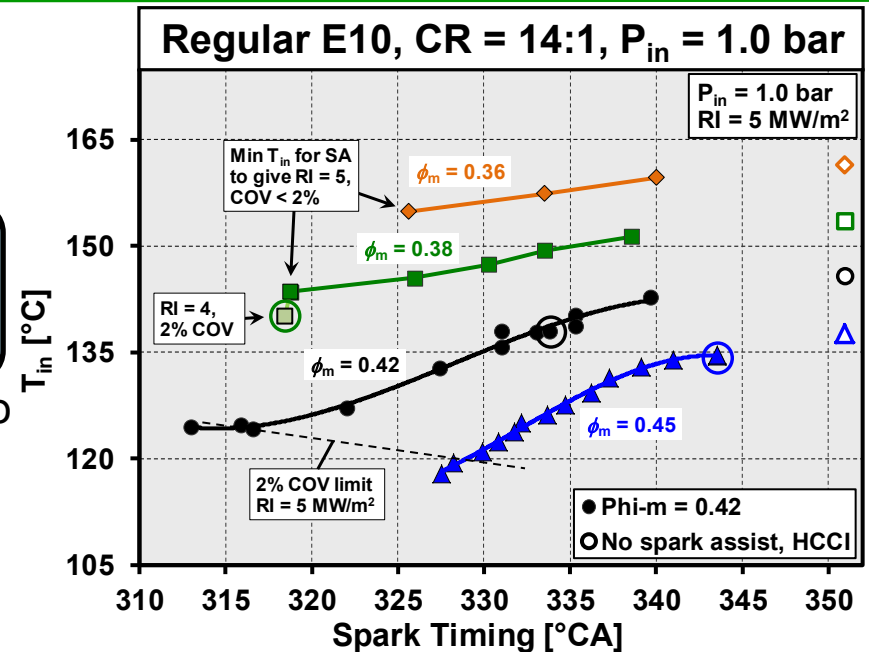
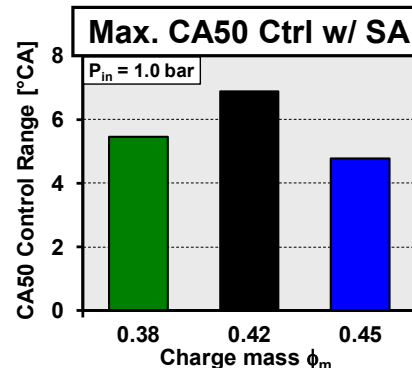
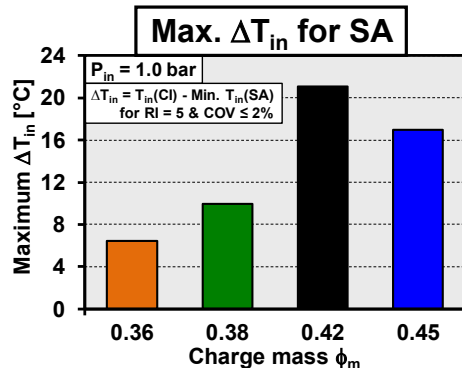
**Spark Assist gives 4 – 7° CA of CA50 control authority.**





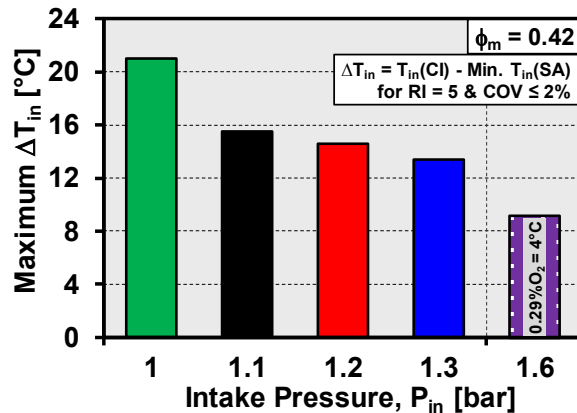
# Effect of $\phi$ on Allowable $T_{in}$ Range for SA

- Higher  $T_{in}$ s are required with decreased  $\phi$ .
  - Lowest  $\phi$  for SA = 0.36  $\Rightarrow$  Can only compensate for small  $T_{in}$  decrease, 6.5°C.
- $T_{in}$  range for effective SA compensation does not vary consistently with  $\phi$ .
  - Max  $\Delta T_{in}$  is at  $\phi = 0.42$ , 21°C for COV < 2%.
  - For  $\phi$ 's = 0.36 & 0.38, min  $T_{in} \Rightarrow$  SA flame too weak to give RI = 5 MW/m<sup>2</sup>, but COV < 2%.
  - At  $\phi = 0.45$ ,  $\Delta T_{MAX} = 17^\circ\text{C}$ , for COV < 2%
    - Small variations in turbulent flame propagation have a large effect on stability of the CI combustion  $\Rightarrow$  near the Knock/Stability limit.
- Range of CA50 control with SA also peaks at  $\phi = 0.42$ .
  - Stronger flame combustion than  $\phi = 0.38$
  - More stable CI combustion than  $\phi = 0.45$



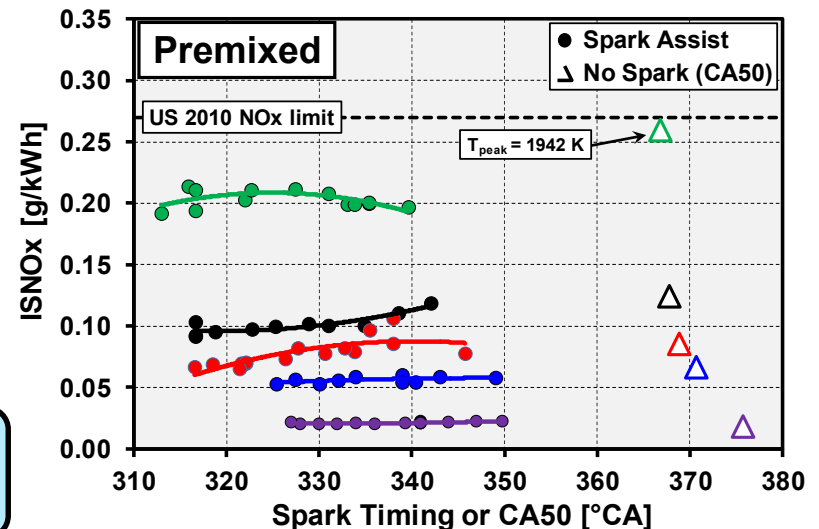
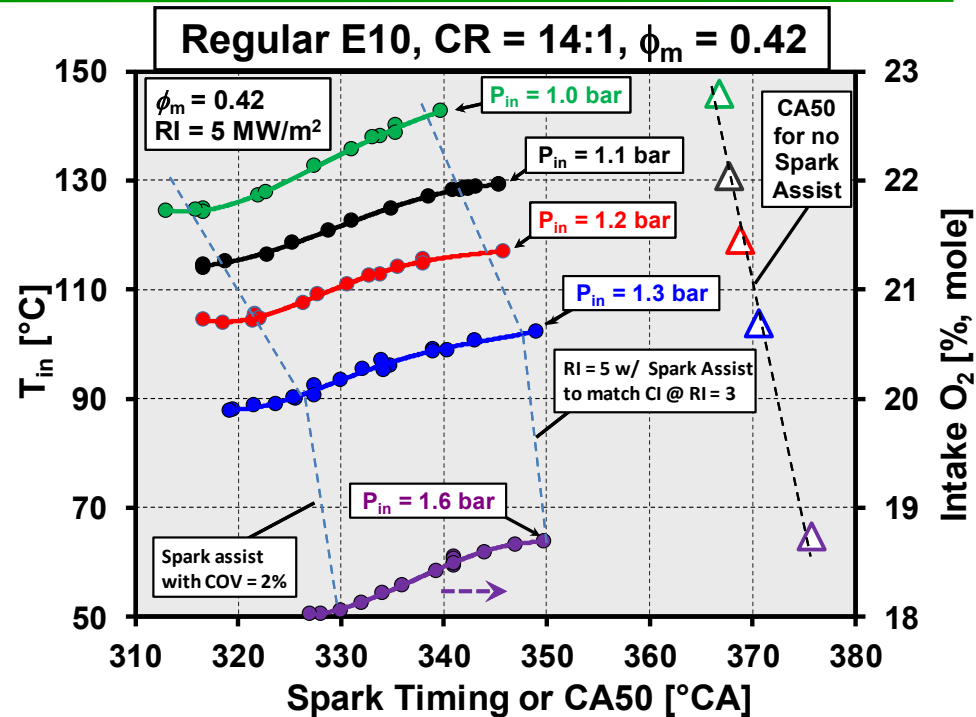
# Effect of $P_{in}$ on Allowable $T_{in}$ Range for SA

- Required  $T_{in}$  decreases with increased boost from  $1.0 \leq P_{in} \leq 1.3$  bar.  
 $\Rightarrow P_{in} = 1.6$  bar,  $T_{in} = 60^\circ\text{C} + \text{EGR}$
- For each  $P_{in}$ , progressively decrease  $T_{in}$  or increase EGR & compensate with SA.
- Trends are very similar for all  $P_{in}$ s.
  - Moderate decrease in the  $\Delta T_{in}$  range for SA compensation with increased  $P_{in}$ .



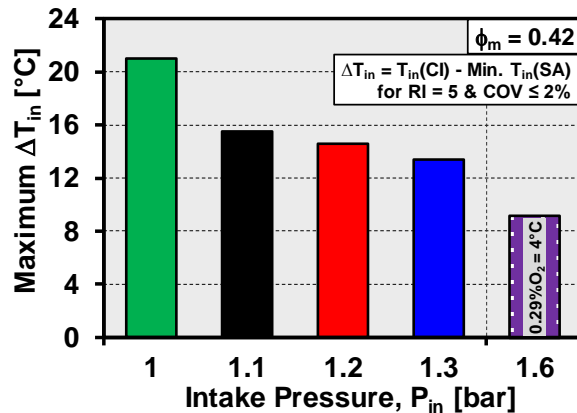
- $\text{NO}_x$  emissions for SA with premixed fueling are about the same or slightly less than CI only. Very low except  $P_{in} = 1.0$  bar.

- SA works well for  $P_{in} = 1.0$  to 1.6 bar.**
  - Potential for SA control at even higher boost.



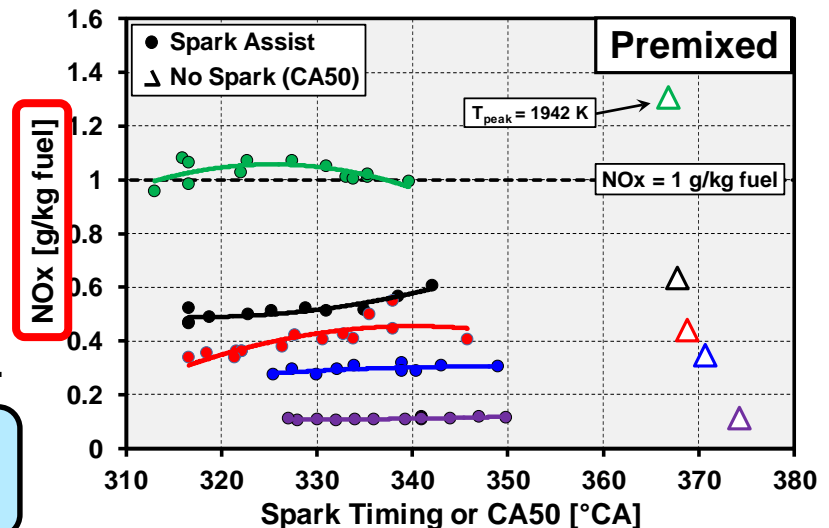
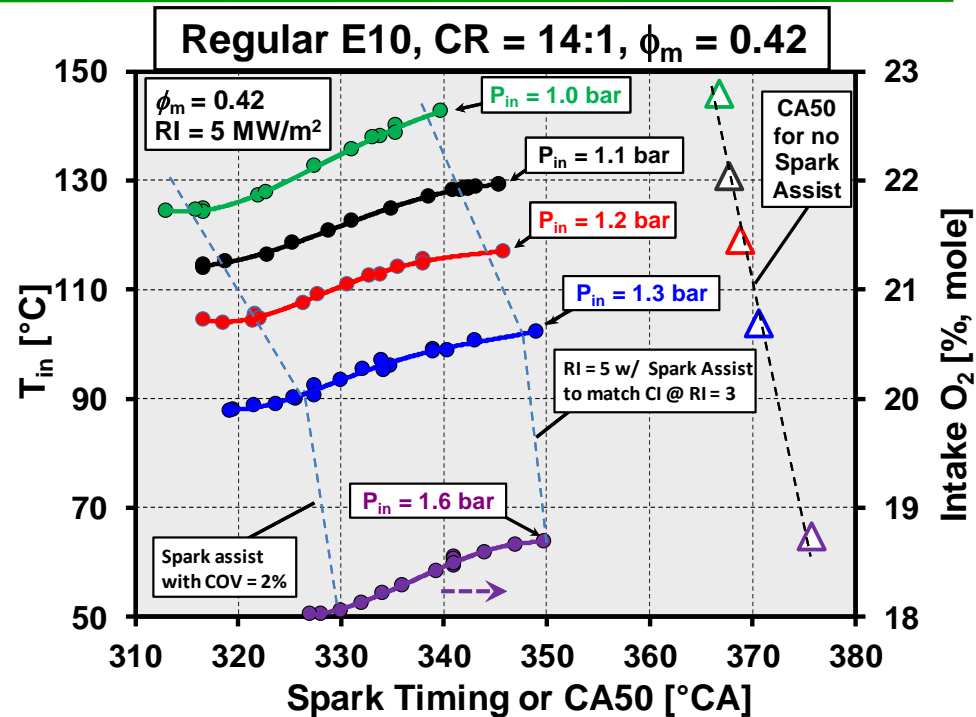
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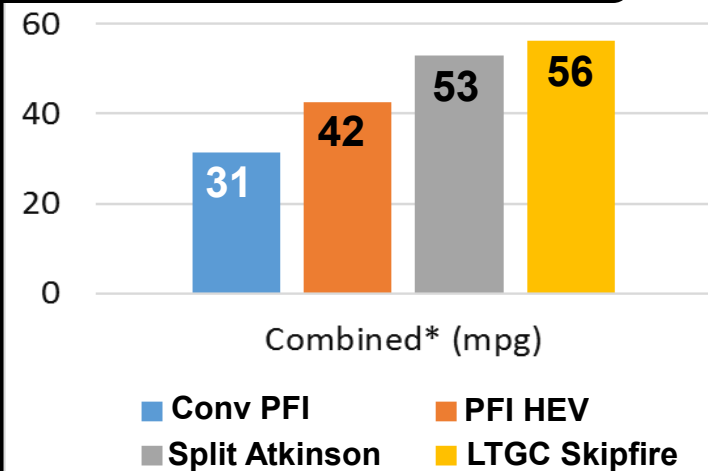
# Brake Efficiency and Vehicle Potential

- **Objective:** Determine Brake Thermal Efficiencies (BTE) of an LTGC engine, and work with ANL to apply to the “Autonomie” vehicle-simulation model.
- Analyze high-efficiency data sets for 1200, 1800, and 2400 rpm at a moderate boost of  $P_{in} = 1.8$  bar absolute for three loads at each speed ( $\sim 6 - 10$  bar IMEP<sub>net</sub>).
- Correct IMEP-gross and indicated TEs for:
  - 1) Pumping work – Compute IMEP-net from experimental data.  
⇒ Greater loss at higher speeds; higher flow intake ports would help.
  - 2) Turbocharger losses – Applied turbocharger model supplied by GM.  
⇒ Greater loss at lower loads for each speed, highest loads have no loss.
  - 3) Friction – Applied friction model supplied by GM, based on Bishop’s work (upgraded and calibrated to FEV bench mark data). ⇒ Moderate increase in loss with speed.

● **Peak TEs decreased from ~50%-indicated to 44%-brake ⇒ Still very good**

- **Autonomie vehicle model**, applied by Ram Vijayagopal & Aymeric Rousseau, ANL
  - Evaluated as a single-motor HEV using skipfire.

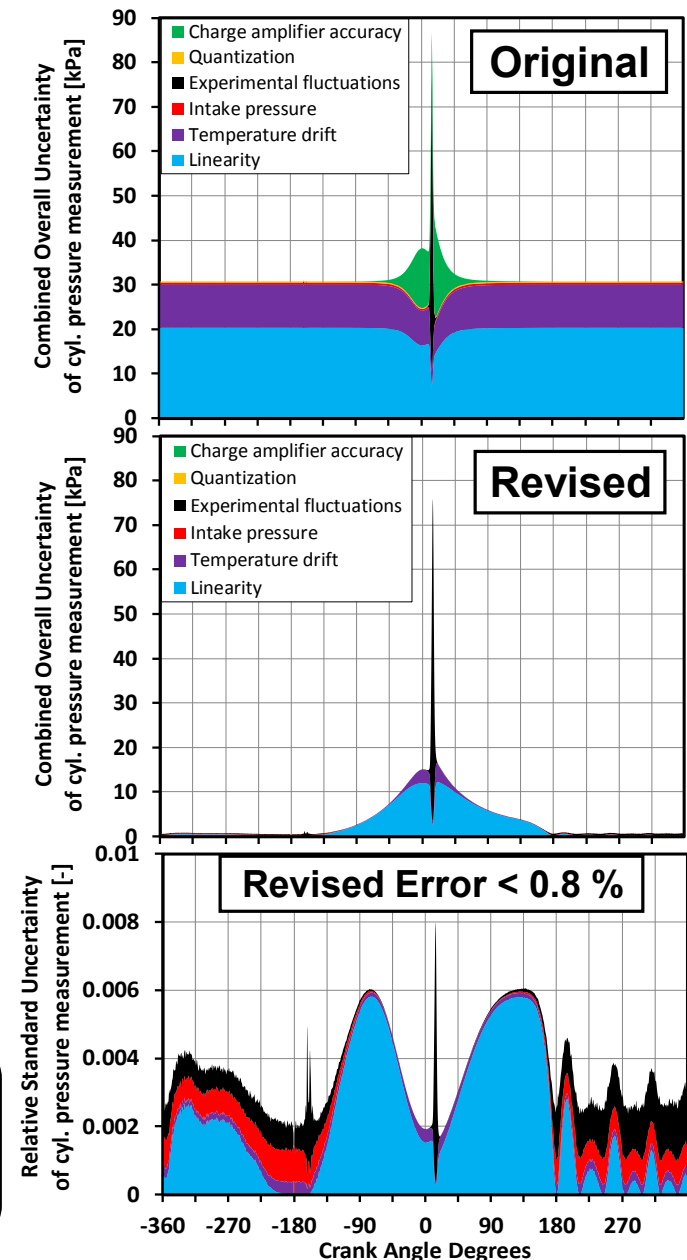
- LTGC configuration improves fuel economy by:
  - **44% over conventional PFI**
  - **25% over PFI single-motor HEV**
  - **6% over Split Atkinson HEV (2 motors, higher cost)**
- Higher BTEs likely w/ engine designed for LTGC.





# Uncertainty Quantification (UQ)

- Data acquisition and analysis are conducted using high-quality equipment & rigorous expr. practices.
- But overall uncertainty not previously quantified.
- Worked with R. Whitesides and G. Petitpas at LLNL to conduct uncertainty analysis of our data.
  - LLNL developed a computational framework for UQ.
  - SNL initially provided manufacturers' uncertainties for the various sensors and components.
- **Original UQ analysis**, based on manufacturers' general specifications, factory calibrations, and generalized assumptions about U application, gave  $\Rightarrow$  **High overall uncertainties**
- We then worked with LLNL to apply actual measured uncertainties of sensors & components and laboratory practices that eliminated or greatly reduced some uncertainties.  $\Rightarrow$  Also provided insight as to how some uncertainties should be applied.
- **Revised UQ analysis (in progress)**, based on actual values and more detailed methodology shows  $\Rightarrow$  **Much lower uncertainties, 0.6 – 0.8 % max.**

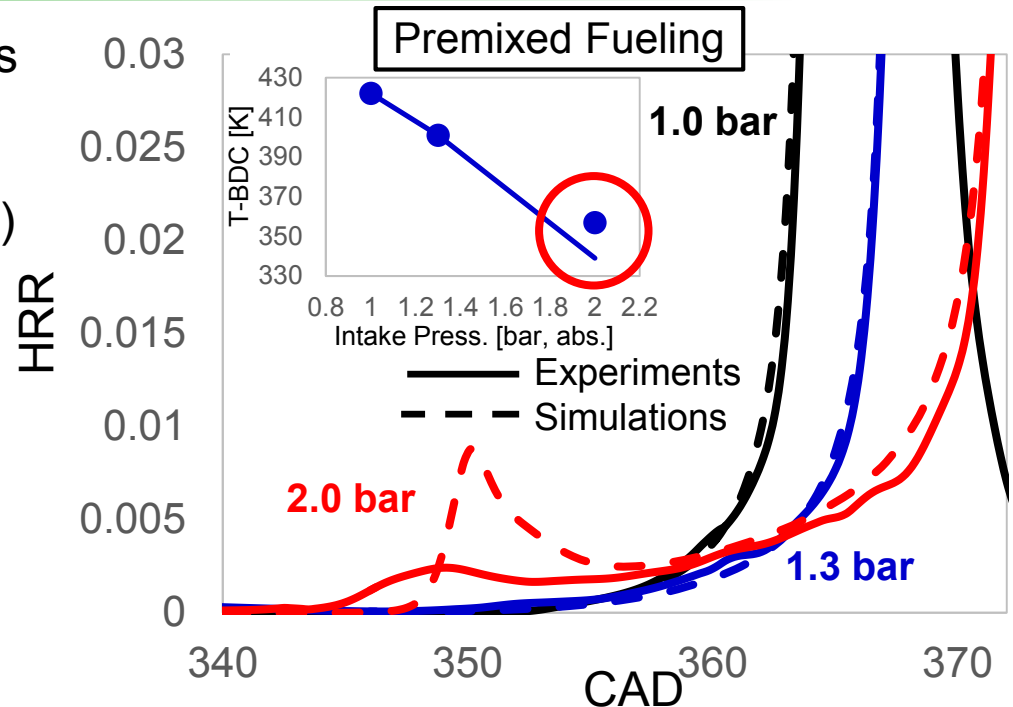




# Sandia Experimental Data Allows LLNL to Test Kinetic Model for E10 Gasoline

- 5-component gasoline surrogate has been proposed by LLNL to simulate the ignition behavior of a reference gasoline, RD5-87 (Reg-E10, 87 AKI)

Mole %		
Class	RD587	Surrogate
Paraffins	16.3%	15.0%
Iso-paraffins	23.6%	35.0%
Cyclo-alkanes	12.2%	/
Aromatics	21.1%	23.0%
Olefins	5.8%	6.0%
Ethanol	19.9%	21.0%



Simulations: Cernansky\*, Mehl and Pitz, LLNL  
\* on sabbatical from Drexel University

- $T_{BDC}$  was varied to match the CA50 of the simulations with CA10 of the experiments (simulating the adiabatic core, i.e. hottest zone).
- Comparison shows surrogate is slightly deficient at 2.0 bar  $\Rightarrow T_{BDC-sim} < T_{BDC-expr.}$   
 $\Rightarrow$  Indicates surrogate composition may need modification, e.g. add cyclo-alkanes.
- Simulated HRR profiles are generally consistent with the experimental data.
  - At  $P_{in} = 2.0$  bar, they exhibit the onset of an LTHR event rapidly degenerating into ITHR.
  - At  $P_{in} = 1.0$  & 1.3 bar, they exhibit no LTHR, and the ITHR matches well with experiments.



# Response to Reviewer Comments

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- **Reviewers made positive comments about our shift of focus to combustion-timing control rather than improved efficiency.**
  - We appreciate these positive comments, and are continuing to make good progress on both DDI-PFS (DI fuel-injection strategies) & Spark-Assist for combustion timing control  $\Rightarrow$  see accomplishments slides.
- **Work should be integrated with Co-Optima to study fuel effects under realistic LTGC conditions & understand whether Octane Index (OI) & K-factor is an appropriate metric.**
  - This project is not part of Co-optima, but we have modest funding from Co-Optima to conduct fuels tests, as mentioned on the Collaborations slide. Current efforts focus on the performance of gasolines with high RON and Sensitivity (for boosted SI engines) for LTGC engines. These data are being integrated with data from our existing fuels database for LTGC to evaluate the use of OI and K-factor, among other things. These results will be reported in our Co-Optima AMR presentation on Thursday, June 8, 2017.
- **Two reviewers asked about the  $\phi$ -sensitivity of market fuels, needed for DDI-PFS control.**
  - We have tested three different regular-grade gasolines (one E0 and two E10), and all exhibited good  $\phi$ -sensitivity. Delphi has tested at least two other fuels that work well.  $\phi$ -sensitivity appears to be very common, maybe universal, for regular-grade E0 & E10 fuels. Ultimately, a simple test would be needed, analogous to a RON or MON test, to guarantee that all market fuels have sufficient  $\phi$ -sensitivity.
- **Should compute estimated Brake TEs to account for friction and turbocharger effects.**
  - As reported in this presentation, we have applied Friction and Turbocharger models from GM and accounted for pumping work to compute BTEs for nine speed/load conditions. Peak TEs decreased from ~50%-indicated to 44%- brake, which is still quite good.
- **An Uncertainty Quantification (UQ) analysis should be performed.**
  - We have collaborated with LLNL to perform a UQ analysis as reported in this presentation.
- **Multiple reviewers suggested that a 3-D CFD modeling effort would be valuable.**
  - We completely agree. We have tried to promote collaborative modeling efforts without dedicated funding, at LLNL, UC-Berkeley, and GM, with very limited success. A dedicated 3-D CFD modeling effort, similar to the diesel projects, would greatly enhance our ability to make progress on DDI-PFS & SA for CA50 control.



# Collaborations

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- Project is conducted in close cooperation with U.S. Industry through the **Advanced Engine Combustion (AEC) / HCCI Working Group**, under a memorandum of understanding (MOU).
  - Twelve OEMs, Three energy companies, Six national labs, & Several universities.
- **General Motors**: Bimonthly internet meetings  $\Rightarrow$  presentations and in-depth discussions on recent research.  $\Rightarrow$  GM provided guidance on OI & K-factor analysis.
  - GM provided friction and turbocharger models for BTE analysis.
- **ANL**: Worked w/ ANL to determine potential vehicle fuel-economy improvement for an LTGC engine HEV compared to various SI engine types/HEV-configs.
- **LLNL**: Collaborate on UQ analysis w/ Whitesides & Petitpas, as reported above.
- **LLNL**: Support development and validation of a chemical-kinetic model for RD5-87 (87-AKI, E10 gasoline) with Mehl and Pitz, as reported above.

## **DOE-OVT project is also leveraged through three related research efforts**

- **Co-Optima Fuels Project**: Project on advanced fuels for improved performance of LTGC engines, & evaluation of new fuels for boosted-SI engines
- **Chevron**: Project on advanced petroleum-based fuels for LTGC
- **Sandia LDRD**: Project on fuel injection



# Future Work

*Any proposed future work is subject to change based on funding levels*

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**DDI-PFS for CA50 Control:** Works well for  $P_{in} = 1.0$  to 2.4 bar

⇒ Further investigation is warranted.

- Optimize injection strategies to provide good CA50 control, but lower NOx propensity, particularly at lower  $P_{in}$ s.
  - Investigate variations in the early/late split ratio, triple injections, and injector umbrella angle to obtain a more optimal fuel distribution.
  - Lower peak  $\phi$  and a more uniform distribution of fuel in the mid-range  $0.3 \leq \phi \leq 0.6$ .
- Develop 300 bar fuel system ⇒ potential to improve  $\phi$ -dist. for better PFS perform.

**Spark-Assisted (SA) LTGC:**

- Complete mapping of the range of conditions for effective SA with premixed fueling.
- Investigate charge stratification using late-DI fueling to increase the range for effective SA ⇒ increase  $\phi$  limits, CA50 control range, or  $T_{in}$  compensation range.

**Simulated Transients:** Investigate the potential of DDI-PFS and SA to control CA50 through a simulated transient, such as a change in load or speed.

**Thermal Boundary Layer:** Short-term opportunity to apply new linear CARS technique with C. Kliwer (SNL-BES) ⇒ very promising for accurate single-shot BL data.

**Continue to Team with LLNL:**

- UQ analyses: Complete revised UQ of Cyl-Press, new UQ of HRR, emissions, etc.
- Support kinetic model development with data, analysis, and discussions.



# Summary

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## Relevance

- LTGC can provide efficiencies at or above diesel engines  $\Rightarrow$  use light distillates efficiently.
- Rapid control of CA50 through SA or injection strategies is central to developing LTGC.

## Approach

- Use Sandia metal LTGC engine  $\Rightarrow$  designed to allow well controlled experiments.
- Apply DDI-PFS to adjust kinetic rates of autoignition and SA to control combustion timing.
- Team with GM & ANL for BTE and fuel economy, and LLNL for UQ and kinetic models.

## Accomplishments:

- Showed that DDI-PFS can control CA50 up to  $8.5^\circ$  CA, from near misfire (overly retarded) to beyond the knock/ringing limit (overly advanced).
  - Works well from  $P_{in} = 1.0$  bar absolute (naturally aspirated) to 2.4 bar (high boost) for CRs 14:1 & 16:1
- Demonstrated that spark assist (SA) can control CA50 up to  $7^\circ$  CA for well-premixed LTGC and provide increased tolerance to  $T_{in}$  variations, up to  $21^\circ\text{C}$ .
  - SA was shown to be effective for equivalence ratios ( $\phi$ ) from 0.36 to 0.45  $\Rightarrow$  best at  $\phi = 0.42$ .
  - SA works well from  $P_{in} = 1.0$  to 1.6 bar absolute  $\Rightarrow$  potential for even higher boost.
- Computed Brake TEs using GM-supplied friction & turbocharger models.  
 $\Rightarrow$  Peak BTEs were 44%, which is still quite good (Peak Indicated TEs were  $\sim 50\%$ )
  - Worked with ANL to show that LTGC gave the best vehicle fuel economy of all methods examined.
- Collaborated with LLNL to conduct an Uncertainty Quantification analysis.
- Supported LLNL on the development of a kinetic model for RD5-87, a Regular-E10 gasoline  
 $\Rightarrow$  Good match found between model and experimental data.

**Collaborations:** Several collaborations as listed on Collaborations slide  $\Rightarrow$  industry & national labs

**Future work:** *(Any proposed future work is subject to change based on funding levels)*

- Future Work Slide lists a portfolio of studies  $\Rightarrow$  CA50 ctrl, sim'd transients, thermal BL, UQ, kinetic model



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